

F-006

(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau(43) International Publication Date
21 February 2002 (21.02.2002)

PCT

(10) International Publication Number
WO 02/15285 A1(51) International Patent Classification⁷: H01L 31/072,
31/109, 31/0328, 31/0336, 29/76, 29/94

(21) International Application Number: PCT/US01/25259

(22) International Filing Date: 10 August 2001 (10.08.2001)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
09/638,130 11 August 2000 (11.08.2000) US

(71) Applicant and

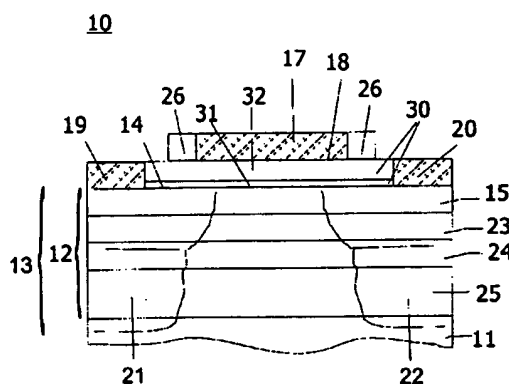
(72) Inventor: BRADDOCK, Walter, David IV [US/US]; 300
First St. N.E., Rochester, MN 55906 (US).(74) Agent: BRADDOCK, Christopher, T.; 217 East Seventh
Avenue, Denver, CO 80203 (US).(81) Designated States (national): AE, AG, AL, AM, AT, AU,
AZ, BA, BB, BG, BR, BY, BZ, CA, CH, CN, CO, CR, CU,CZ, DE, DK, DM, DZ, EC, EE, ES, FI, GB, GD, GE, GH,
GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC,
LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW,
MX, MZ, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK,
SL, TJ, TM, TR, TT, TZ, UA, UG, US, UZ, VN, YU, ZA,
ZW.(84) Designated States (regional): ARIPO patent (GH, GM,
KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZW), Eurasian
patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European
patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE,
IT, LU, MC, NL, PT, SE, TR), OAPI patent (BF, BJ, CF,
CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD,
TG).

Published:

- with international search report
- before the expiration of the time limit for amending the
claims and to be republished in the event of receipt of
amendments

For two-letter codes and other abbreviations, refer to the "Guid-
ance Notes on Codes and Abbreviations" appearing at the begin-
ning of each regular issue of the PCT Gazette.

(54) Title: METAL SULFIDE SEMICONDUCTOR TRANSISTOR DEVICES



WO 02/15285 A1

(57) Abstract: A self-aligned enhancement mode metal-sulfide-compound semiconductor field effect transistor (10) includes a lower sulfide layer that is a mixture of Ga_2S , Ga_2S_3 , and other gallium sulfide compounds (30), and a second insulating layer that is positioned immediately on top of the gallium sulphur layer together positioned on upper surface (14) of a III-V compound semiconductor wafer structure (13). Together the lower gallium sulfide compound layer and the second insulating layer form a gallium sulfide gate insulating structure. The gallium sulfide gate insulating structure and underlying compound semiconductor gallium arsenide layer (15) meet at an atomically abrupt interface at the surface of with the compound semiconductor wafer structure (14). The initial essentially gallium sulphur layer serves to passivate and protect the underlying compound semiconductor surface from the second insulating sulfide layer. A refractory metal gate electrode layer (17) is positioned on upper surface (18) of the second insulating sulfide layer. The refractory metal is stable on the second insulating sulfide layer at elevated temperature. Self-aligned source and drain areas, and source and drain contacts (19, 20) are positioned on the source and drain areas (21, 22) of the device. Multiple devices are then positioned in proximity and the appropriate interconnection metal layers and insulators are utilized in concert with other passive circuit elements to form an integrated circuit structure.

Metal Sulfide Semiconductor Transistor Devices

FIELD OF THE INVENTION

5 The present invention pertains to low power and high speed integrated circuits in the compound semiconductor field utilizing field effect transistors and more specifically complementary field effect transistors used in concert including enhancement mode self-aligned metal-sulfide-compound semiconductor transistors and depletion mode self-aligned metal-sulfide-compound semiconductor transistors and methods of materials growth and
10 fabrication of said structures and the ultra large scale integration of said transistors.

BACKGROUND OF THE INVENTION

 The gallium arsenide and indium phosphide integrated circuit industry has been limited without a technology that simultaneously allows the integration of complementary field effect transistor devices and transistors with low gate leakage currents. In contrast to
15 silicon technology that has a very mature and useful complementary metal oxide semiconductor (CMOS) technology. Field effect transistor (FETs) widely used in the III-V semiconductor industry employ metal gates and Schottky gate contacts that have quiescent-state leakage currents exceeding many microamps. The use of metal gates in compound semiconductor technology further results in individual transistors and integrated
20 circuits that have excessively high power dissipation, reduced transconductance, reduced logic swing and the inability to operate on a single power supply, and generally limited performance characteristics. The high magnitude of the quiescent leakage current limits the maximum integration of GaAs devices to circuits of several hundred thousand transistors for those skilled in the art. In contrast, the simultaneous integration of many millions of
25 transistors is possible at high integration densities using silicon CMOS technology. These ultra high integration densities and levels cannot be obtained using metal, Schottky-style

gates that are not insulated in compound semiconductor FETs. Thus Si CMOS technology offers significant advantages in terms of individual gate leakage, circuit integration level and cost.

However when compared to silicon, complementary GaAs and InP circuit technology
5 exhibits faster and more optimized speed/power performance and efficiency at a low supply voltage of 1V and below. The market acceptance of these GaAs and InP integrated circuit technologies remains low because of the lack of ability to demonstrate high integration densities with low amounts of operating power. Thus, silicon CMOS dominates the field of digital integrated circuitry and neither GaAs nor InP technologies can successfully penetrate
10 this market.

What is needed are new and improved compound semiconductor field effect transistors (FET). What is also needed are new and improved compound semiconductor FETs using metal-sulfide-semiconductor junctions (MSSFET). What is also needed are new and improved compound semiconductor MSSFETs using a self-aligned gate structure. What is
15 also needed are new and improved self-aligned compound semiconductor MSSFETs using enhancement mode and depletion mode operation. What is also needed are new and improved self-aligned compound semiconductor MSSFETs with stable and reliable device operation. What is also needed are new and improved self-aligned compound semiconductor MSSFETs which enable optimum compound semiconductor device performance. What is also needed
20 are new and improved self-aligned compound semiconductor MSSFETs with optimum efficiency and output power for RF and microwave applications. What is also needed are new and improved self-aligned compound semiconductor MSSFETs for use in complementary circuits and architectures. What is also needed are new and improved self-aligned compound semiconductor MSSFETs for low power/high performance complementary circuits and
25 architectures. What is also needed are new and improved self-aligned compound

semiconductor MSSFETs which offer the design flexibility of complementary architectures. What is also needed are new and improved self-aligned compound semiconductor MSSFETs which keep interconnection delays in ultra large scale integration under control. What is needed are new and useful complementary integrated circuits where each individual transistor

5 has a leakage current approaching 10^{-12} amp. What is needed is a truly useful integrated circuit technology for GaAs and InP that allows for the useful and economical operation of ULSI digital integrated circuits in compound semiconductors. What is needed are new and improved compound semiconductor MSSFET integrated circuits with very low net power dissipation. What is needed are new and improved compound semiconductor MSSFET

10 devices with low gate leakage currents that may be integrated together to form ultra large scale integrated circuits that include millions of transistors. What is needed are new and improved complementary MSSFET devices and circuits in compound semiconductors that allow the direct use, transfer and application of silicon CMOS design that already exists in the art.

15 What is also needed are new and improved methods of fabrication of self-aligned compound semiconductor MSSFETs. What is also needed is new and improved methods of fabrication of self-aligned compound semiconductor MSSFETs which are compatible with established complementary GaAs heterostructure FETs technologies. What is also needed are new and improved compound semiconductor MSSFETs which are relatively easy to

20 fabricate and use.

BRIEF DESCRIPTION OF THE DRAWINGS

A more complete understanding of the present invention may be derived by referring to the detailed description and claims when considered in connection with the figures, wherein like reference numbers refer to similar items throughout the figures, and:

25 FIG. 1 is simplified cross sectional view of a self-aligned enhancement mode compound

semiconductor MSSFET in accordance with a preferred embodiment of the present invention;
FIG. 2 is a simplified flow chart illustrating a method of manufacturing a self-aligned enhancement mode compound semiconductor MSSFET in accordance with a preferred embodiment of the present invention.

5 The exemplification set out herein illustrates a preferred embodiment of the invention in one form thereof, and such exemplification is not intended to be construed as limiting in any manner.

DETAILED DESCRIPTION OF THE DRAWINGS

The present invention provides, among other things, a self-aligned enhancement mode
10 metal-sulfide-compound semiconductor FET. The FET includes a gallium sulphur insulating structure that is composed of at least two distinct layers. The first layer is most preferably more than 10 angstroms thick but less than 25 angstroms in thickness and composed substantially of gallium sulphur compounds including but not limited to stoichiometric Ga_2S_3 , GaS , and Ga_2S , and possibly a lesser fraction of other gallium sulphur compounds. The upper
15 insulating layer in the gallium sulfide insulating structure is composed of an insulator that does not intermix with the underlying gallium sulphide insulating structure. This upper layer must possess excellent insulating qualities, and is most typically composed of gallium sulphur and a third rare earth element that together form a ternary insulating material. Therefore the entire gallium sulfide rare earth gate insulator structure is composed of at least
20 two layers and may contain a third intermediate graded layers that consists of a mixture of the upper insulating material and the gallium sulphur compounds that compose the initial layer. Together the initial gallium sulphur layer, any intermediate graded layer and the top insulating region form both a gallium sulfide insulating structure and the gate insulator region of a metal-sulfide-compound semiconductor field effect transistor. The initial substantially
25 gallium sulphur layer forms an atomically abrupt interface with the top layer of the

compound semiconductor wafer structure, and does not introduce midgap surface states into the compound semiconductor material. A refractory metal gate electrode is preferably positioned on the upper surface of the gate insulator structure layer. The refractory metal is stable on the gate insulator structure layer at elevated temperature. Self-aligned source and drain areas, and source and drain contacts are positioned on the source and drain areas. In all embodiments preferred and otherwise, the metal-sulfide-compound semiconductor transistor includes multi-layer gate insulator structure including an initial gallium sulphur layer, intermediate transition layer, and upper insulating layer of 30-250 angstroms in thickness positioned on upper surface of a compound semiconductor heterostructure that form the gate insulator structure. The preferred embodiment also comprises a compound semiconductor heterostructure including a GaAs, $\text{Al}_x\text{Ga}_{1-x}\text{As}$ and $\text{In}_y\text{Ga}_{1-y}\text{As}$ layers with or without n-type and/or p-type charge supplying layers which are grown on a compound semiconductor substrate, a refractory metal gate of W, WN, or WSi, self aligned donor (n-channel FET) or acceptor (p-channel FET) implants, and source and drain ohmic contacts. In another preferred embodiment, the compound semiconductor heterostructure comprises an $\text{In}_y\text{Ga}_{1-y}\text{As}$, $\text{Al}_x\text{In}_{1-x}\text{As}$, and InP compound semiconductor heterostructure and n-type and/or p-type charge supplying layers which are grown on an InP substrate, and a refractory metal gate of W, WN, or WSi, self aligned donor (n-channel FET) or acceptor (p-channel FET) implants, and source and drain ohmic contacts.

FIG. 1 is simplified cross sectional view of a self-aligned enhancement mode compound semiconductor MSSFET in accordance with a preferred embodiment of the present invention. Device 10 includes a compound semiconductor material, such as any III-V material employed in any semiconductor device, represented herein by a III-V semiconductor substrate 11 and a compound semiconductor epitaxial layer structure 12. For the purpose of this disclosure, the substrate 11 and any epitaxial layer structure 12 formed thereon will be

referred to simply as a compound semiconductor wafer structure which in FIG. 1 is designated 13. Methods of fabricating semiconductor wafer structure 13 include, but are not limited to, molecular beam epitaxy (MBE) and metal organic chemical vapor deposition (MOCVD). It will of course be understood that in some specific applications, there may be
5 no epitaxial layers present and upper surface of top layer 15 may simply be the upper surface of substrate 11.

Device 10 further comprises a gate insulator structures (30) that includes at least two or more layers. The first layer of the gate insulator structure (31) is composed entirely of gallium sulfide compounds and is directly adjacent to and deposited upon the compound
10 semiconductor structure. The second layer of the gate insulator structure (32) is composed of a compound of gallium, sulphur, and one or more rare earth elements from the periodic table. The initial gallium sulphur layer (31) forms an atomically abrupt interface 14 with the upper surface of top layer 15, the top layer of the compound semiconductor structure. A refractory metal gate electrode 17 which is stable in the presence of top insulating material at elevated
15 temperature is positioned on upper surface 18 of the gate insulator structure. Dielectric spacers 26 are positioned to cover the sidewalls of metal gate electrode 17. Source and drain contacts 19 and 20 are deposited on self-aligned source and drain areas 21 and 22, respectively.

In a specific embodiment, the compound semiconductor epitaxial layer structure
20 consists of a <11 angstrom GaAs top layer (15), a <101 angstrom $\text{Al}_x\text{Ga}_{1-x}\text{As}$ spacer layer (23), a <251 angstrom $\text{In}_y\text{Ga}_{1-y}\text{As}$ channel layer (24), and a GaAs buffer layer (25) grown on a GaAs substrate (11). Top GaAs layer (15) is used to form an atomically abrupt layer with the gate insulator structure with an abrupt interface with low defect density.

As a simplified example of fabricating a self-aligned enhancement mode compound
25 semiconductor MSSFET in accordance with a preferred embodiment of the present invention,

a III-V compound semiconductor wafer structure 13 with an atomically ordered and chemically clean upper surface of top layer 15 is prepared in an ultra-high vacuum semiconductor growth chamber and transferred via a ultra high vacuum transfer chamber to a second ultra high vacuum sulfide and insulator deposition chamber. The initial gallium sulphur layer (31) is deposited on upper compound semiconductor surface layer 15 using thermal evaporation from a high purity Ga_2S_3 source or from crystalline gadolinium gallium sulphide, $\text{Ga}_3\text{Gd}_5\text{S}_{12}$. This initial gallium sulphur layer is deposited while holding the substrate temperature of the compound semiconductor structure at $<500^\circ\text{C}$, and most preferably at a substrate temperature $<395^\circ\text{C}$. After the deposition of approximately 18 angstroms of gallium sulphur compounds in the insulator deposition chamber over a 5 to 8 minute period of time, deposition of the second insulator layer is initiated. The deposition of the second insulator layer starts by directing the flux from a low power sulphur plasma source into the ultra high vacuum system such that the sulphur plasma effluent and species are largely directed toward and impinging upon said compound semiconductor structure with initial gallium sulphide layer. The flux from the sulphur plasma source should be directed at the surface for between 2-5 seconds, subsequently followed by the co-evaporation of gallium sulphur compounds from Ga_2S_3 and a second thermal evaporation source that contains a rare-earth element. The flux beams from the sulphur source, Ga_2S_3 and rare-earth evaporation source thermal evaporation sources are carefully balanced to provide a ternary insulator layer on top of the initial gallium sulphide layer on said compound semiconductor structure. As the deposition of the second ternary insulator layer is initiated, the substrate temperature is simultaneously adjusted to provide an optimized substrate temperature for the deposition of this layer. In this example the substrate temperature required to deposit the gallium+sulphur+rare earth layer is $<530^\circ\text{C}$. The deposition of this second insulator layer proceeds until the total insulator thickness of 200-250 angstroms is achieved. Shutters and

valves are utilized to stop the deposition of the ternary gallium+sulphur+rare earth layer upon the deposition of the required thickness of the insulator layer. The substrate temperature is cooled in-vacuum to $<200^{\circ}\text{C}$, and the deposition of a refractory metal which is stable and does not interdiffuse with on the top layer of the gate insulator structure at elevated

5 temperature such as WSi or WN is deposited on upper surface 18 of sulfide layer 32 and subsequently patterned using standard lithography. The refractory metal layer is etched until sulfide layer 31 is exposed using a refractory metal etching technique such as a fluorine based dry etching process. The refractory metal etching procedure does not etch the sulfide layer 31, thus, sulfide layer 31 functions as an etch stop layer such that upper surface of top layer

10 15 remains protected by sulfide layer 31. All processing steps are performed using low damage plasma processing. Self-aligned source and drain areas 21 and 22, respectively are realized by ion implantation of Si (n-channel device) and Be/F or C/F (p-channel device) using the refractory metal gate electrode 17 and the dielectric spacers 26 as implantation masks. Such ion implantation schemes are compatible with standard processing of

15 complementary compound semiconductor heterostructure FET technologies and are well known to those skilled in the art. The implants are activated at $700\text{-}900^{\circ}\text{C}$ using rapid thermal annealing in an ultra high vacuum environment such that degradation of the interface 16 established between top layer 15 and sulfide layer 31 is completely excluded. Finally, ohmic source and drain contacts 19 and 20 are deposited on the self-aligned source and drain areas

20 21 and 22, respectively. The devices may then be interconnected using the standard methods to those skilled in the art of integrated microelectronics and integrated circuit manufacture.

FIG. 2 is a simplified flow chart illustrating a method of manufacturing a self-aligned enhancement mode compound semiconductor MSSFET in accordance with a preferred embodiment of the present invention. In step 102, a compound semiconductor wafer structure

25 is produced using standard epitaxial growth methods in the art. In step 103, a layer consisting

of gallium sulphide compounds including but not limited to Ga_2S_3 , Ga_2S , GaS is deposited on upper surface of said compound semiconductor wafer structure. In step 104, an insulating layer of gallium sulphide and one or more rare earth elements is deposited on the upper surface of the initial gallium sulphide compound layer. The gallium sulfide gate insulator structure is formed in steps 104 and 105. In step 106, a stable refractory gate metal is positioned on upper surface of said gate insulator structure. In step 108, source and drain ion implants are provided self-aligned to the gate electrode. In step 110, source and drain ohmic contacts are positioned on ion implanted source and drain areas.

In a preferred embodiment, step 100 provides a compound semiconductor substrate such as $GaAs$ or InP . Step 102 includes the preparation and epitaxial growth of an atomically ordered and chemically clean upper surface of the compound semiconductor wafer structure. Step 103 preferably comprises thermal evaporation from a purified and crystalline gadolinium gallium sulphide or Ga_2S_3 source on an atomically ordered and chemically clean upper surface of the compound semiconductor wafer structure. Step 104 comprises the formation of a gallium+sulphide+rare earth elemental insulating layer formed through the simultaneous vacuum evaporation of gallium sulphur species and at least one rare earth element such as Gadolinium with the simultaneous sulphidization using the effluent of an sulphur gas plasma source directed in simultaneous combination with other thermal evaporation sources toward substrate 100. The initial gallium sulphur compound layer of the gate insulator structure preferably functions as an etch stop layer such that the upper surface of the compound semiconductor wafer structure remains protected by the gate sulfide during and after gate metal etching. The refractory gate metal desirably does not react with or diffuse into the gate sulfide layer during high temperature annealing of the self-aligned source and drain ion implants. The quality of the interface formed by the gate sulfide layer and the upper surface of the compound semiconductor structure is desirably preserved during high

temperature annealing of the self-aligned source and drain ion implants. The self-aligned source and drain implants are desirably annealed at approximately 700°C in an ultra high vacuum environment. The self-aligned source and drain implants are desirably realized by positioning dielectric spacers on the sidewalls of the refractory gate metal.

5 Thus, new and improved compound semiconductor devices and methods of fabrication are disclosed. The new and improved self-aligned enhancement mode metal-sulfide-compound semiconductor heterostructure field effect transistors enable stable and reliable device operation, provide optimum compound semiconductor device performance for low power/high performance complementary circuits and architectures, keep interconnection
10 delay in ULSI under control, and provide optimum efficiency and output power for RF and microwave applications as well as for digital integrated circuits that require very high integration densities.

 These improvements essentially solve or overcome the problems of the prior art, such as high gate leakage in compound semiconductor FET devices, low integration densities, dc
15 electrical instability, and electrical hysteresis, and therefore provide a highly useful invention. While we have shown and described specific embodiments of the present invention, further modifications and improvements will occur to those skilled in the art. We desire it to be understood, therefore, that this invention is not limited to the particular forms shown and we intend in the appended claims to cover all modifications that do not depart from the spirit and
20 scope of this invention.

What is claimed:

1. An enhancement mode metal-sulfide-compound semiconductor field effect transistor comprising:
a compound semiconductor wafer structure having an upper surface;
5 a layer composed of the compounds of gallium and sulphur including but not limited to mixtures of Ga_2S_3 , Ga_2S , GaS and other gallium sulphur compounds positioned on upper surface of said compound semiconductor wafer structure;
a second insulating layer composed of the compounds of gallium and sulphur and at least one or more rare earth elements that form an insulating layer deposited on top of the initial
10 supporting gallium sulphur layer, with said first and second layers forming a gate insulator structure adjacent to and on top of the compound semiconductor structure;
a stable refractory metal gate electrode positioned on upper surface of said gate insulator structure layers;
source and drain ion implants self-aligned to the gate electrode; and
15 source and drain ohmic contacts positioned on ion implanted source and drain areas;
wherein the refractory metal gate electrode comprises a refractory metal selected from the group consisting of W, WN or WSi or combinations thereof;
means of interconnection of said transistors forming a monolithically integrated circuit.
2. An enhancement mode metal-sulfide-compound semiconductor field effect transistor as
20 claimed in claim 1 wherein the initial layer of gallium sulphur compounds forms an atomically abrupt interface with the upper surface of the compound semiconductor wafer structure.
3. An enhancement mode metal-sulfide-compound semiconductor field effect transistor as
claimed in claim 1 wherein the gate insulator structure is composed of three layers, an initial
25 gallium sulphur compound layer, a graded layer that contains varying compositions of

gallium sulphur and at least one rare-earth element, and a third insulator layer that is composes largely of a compound of gallium, sulphur and one or more rare earth elements.

4. An enhancement mode metal-sulfide-compound semiconductor field effect transistor as claimed in claim 1 wherein the gate insulator structure is composed of more than three multiple layers, an initial gallium sulphur compound layer, and multiple layers containing gallium and sulphur with or without the inclusion of one or more rare earth elements that together form an insulating gallium sulfide gate insulator structure.
5. An enhancement mode metal-sulfide-compound semiconductor field effect transistor as claimed in claim 1 wherein the initial gallium sulphur compound layer has a thickness of more than 10 angstroms and less than 25 angstroms.
6. An enhancement mode metal-sulfide-compound semiconductor field effect transistor as claimed in claim 1 wherein the gate insulator structure has an overall total thickness of 20-300 angstroms.
7. An enhancement mode metal-sulfide-compound semiconductor field effect transistor as claimed in claim 1 wherein the initial gallium sulphur compound layer forms an atomically abrupt interface with the compound semiconductor structure that extend less than four atomic layers in depth of structural interface modulation.
8. An enhancement mode metal-sulfide-compound semiconductor field effect transistor as claimed in claim 1 wherein the initial gallium and sulphur compound layer and the gate insulator structure protects the upper surface of the compound semiconductor wafer structure.
9. An enhancement mode metal-sulfide-compound semiconductor field effect transistor as claimed in claim 1 wherein the refractory metal gate electrode comprises a refractory metal which is stable in presence of the top layer of the gate insulator structure at an elevated temperature of 700°C and above.
10. An enhancement mode metal-sulfide-compound semiconductor field effect transistor as

claimed in claim 1 wherein the source and drain ion implants comprising said enhancement mode metal-sulfide-compound semiconductor field effect transistor being an n-channel device or p-channel device.

11. An enhancement mode metal-sulfide-compound semiconductor field effect transistor as
5 claimed in claim 1 wherein the source and drain ion implants comprise and Be/F or C/F, said enhancement mode metal-sulfide-compound semiconductor field effect transistor being a p-channel device.

12. An enhancement mode metal-sulfide-compound semiconductor field effect transistor as
10 claimed in claim 1 wherein the upper surface of the compound semiconductor wafer structure comprises GaAs.

13. An enhancement mode metal-sulfide-compound semiconductor field effect transistor as
claimed in claim 1 wherein the upper surface of the compound semiconductor wafer structure comprises $\text{In}_x\text{Ga}_{1-x}\text{As}$.

14. An enhancement mode metal-sulfide-compound semiconductor field effect transistor
15 comprising:
a compound semiconductor wafer structure having an upper surface;
a layer composed of the compounds of gallium and sulphur compounds including but not
limited to mixtures of Ga_2S_3 , Ga_2S and other gallium sulphur compounds positioned on upper
surface of said compound semiconductor wafer structure;
20 a second insulating layer deposited upon the first composed of the compounds of gallium and
sulphur and at least one or more rare earth elements such that the normalized relative
composition of gallium, sulphur, and one or more rare earth elements are changing in a
monotonic manner as a function of the thickness within said insulating layer;
a third insulating layer deposited on top of said second layer composed of gallium sulphur
25 and at least one or more rare earth elements wherein said first, second and third layers form a

gate insulator structure adjacent to and deposited on top of the compound semiconductor structure;

a stable refractory metal gate electrode positioned on upper surface of said gate insulator structure layers;

5 source and drain ion implants self-aligned to the gate electrode; and

source and drain ohmic contacts positioned on ion implanted source and drain areas;

wherein the refractory metal gate electrode comprises a refractory metal selected from the group consisting of W, WN or WSi or combinations thereof;

means of interconnection of said transistors forming a monolithic integrated circuit.

10 15. An enhancement mode metal-sulfide-compound semiconductor field effect transistor as claimed in claim 14 wherein the initial layer of gallium sulphur compounds forms an atomically abrupt interface with the upper surface of the compound semiconductor wafer structure.

16. An enhancement mode metal-sulfide-compound semiconductor field effect transistor as
15 claimed in claim 14 wherein the gate insulator structure is composed of three or more layers, an initial gallium sulphur compound layer, a graded layer that contains varying compositions of gallium sulphur and at least one rare-earth element, and a third insulator layer that is composed largely of a compound of gallium, sulphur and one or more rare earth elements.

17. An enhancement mode metal-sulfide-compound semiconductor field effect transistor as
20 claimed in claim 14 wherein the initial gallium sulphur compound layer has a thickness of more than 10 angstroms and less than 25 angstroms.

18. An enhancement mode metal-sulfide-compound semiconductor field effect transistor as claimed in claim 14 wherein the gate insulator structure has an overall total thickness of 20-300 angstroms.

19. An enhancement mode metal-sulfide-compound semiconductor field effect transistor as claimed in claim 14 wherein the initial gallium sulphur compound layer forms an atomically abrupt interface with the compound semiconductor structure that extend less than four atomic layers in depth of modulation of said interface.
- 5 20. An enhancement mode metal-sulfide-compound semiconductor field effect transistor as claimed in claim 14 wherein the initial gallium and sulphur compound layer and the gate insulator structure protects the upper surface of the compound semiconductor wafer structure.
21. An enhancement mode metal-sulfide-compound semiconductor field effect transistor as claimed in claim 14 wherein the refractory metal gate electrode comprises a refractory metal
- 10 which is stable in presence of the top layer of the gate insulator structure at an elevated temperature of 700°C and above.
22. An enhancement mode metal-sulfide-compound semiconductor field effect transistor as claimed in claim 14 wherein the source and drain ion implants comprising said enhancement mode metal-sulfide-compound semiconductor field effect transistor being an n-channel
- 15 device.
23. An enhancement mode metal-sulfide-compound semiconductor field effect transistor as claimed in claim 14 wherein the source and drain ion implants comprise Be/F and C/F, said enhancement mode metal-sulfide-compound semiconductor field effect transistor being a p-channel device.
- 20 24. An enhancement mode metal-sulfide-compound semiconductor field effect transistor as claimed in claim 14 wherein the upper surface of the compound semiconductor wafer structure comprises GaAs.
- 25 25. An enhancement mode metal-sulfide-compound semiconductor field effect transistor as claimed in claim 14 wherein the upper surface of the compound semiconductor wafer structure comprises $\text{In}_x\text{Ga}_{1-x}\text{As}$.

26. An enhancement mode metal-sulfide-compound semiconductor field effect transistor comprising:

a compound semiconductor wafer structure having an upper surface;

a multilayer gate insulator structure composed of alternating layers comprised of gallium,

5 sulphur, at least one rare-earth element forming a gate insulator with low electronic midgap defect density positioned on upper surface of said compound semiconductor wafer structure;

a stable refractory metal gate electrode positioned on upper surface of said gate insulator structure layer;

source and drain ion implants self-aligned to the gate electrode; and

10 source and drain ohmic contacts positioned on ion implanted source and drain areas,

wherein dielectric spacers are positioned on sidewalls of the stable refractory gate metal electrode.

27. An enhancement mode metal-sulfide-compound semiconductor field effect transistor comprising:

15 a compound semiconductor wafer structure having an upper surface;

a gate insulator structure positioned on upper surface of said compound semiconductor wafer structure;

a stable refractory metal gate electrode positioned on upper surface of said gate insulator structure;

20 source and drain ion implants self-aligned to the gate electrode; and

source and drain ohmic contacts positioned on ion implanted source and drain areas,

wherein the compound semiconductor wafer structure comprises a wider band gap spacer layer and a narrower band gap channel layer.

28. An enhancement mode metal-sulfide-compound semiconductor field effect transistor as

25 claimed in claim 27 wherein the wider band gap spacer layer is positioned between the gate

sulfide layer and the narrower band gap channel layer.

29. An enhancement mode metal-sulfide-compound semiconductor field effect transistor as claimed in claim 27 wherein the wider band gap spacer layer has a thickness of between 3-200 angstroms

5 30. An enhancement mode metal-sulfide-compound semiconductor field effect transistor as claimed in claim 27 wherein the wider band gap spacer layer comprises either $\text{Al}_x\text{Ga}_{1-x}\text{As}$, InP, or $\text{In}_z\text{Ga}_{1-z}\text{P}$ or a combination thereof.

31. An enhancement mode metal-sulfide-compound semiconductor field effect transistor as claimed in claim 27 wherein the narrower band gap channel layer has a thickness of 10-300
10 angstroms.

32. An enhancement mode metal-sulfide-compound semiconductor field effect transistor as claimed in claim 27 wherein the narrower band gap channel layer is positioned between the wider band gap spacer layer and a buffer layer.

33. An enhancement mode metal-sulfide-compound semiconductor field effect transistor as
15 claimed in claim 27 wherein the narrower band gap channel layer comprises $\text{In}_y\text{Ga}_{1-y}\text{As}$.

34. An enhancement mode metal-sulfide-compound semiconductor field effect transistor comprising:

a compound semiconductor wafer structure having an upper surface;

a gate insulator structure positioned on upper surface of said compound semiconductor wafer
20 structure;

a stable refractory metal gate electrode positioned on upper surface of said gate insulator structure layer;

source and drain ion implants self-aligned to the gate electrode; and

source and drain ohmic contacts positioned on ion implanted source and drain areas,

25 wherein the compound semiconductor wafer structure comprises a $\text{Al}_x\text{Ga}_{1-x}\text{As}$, $\text{In}_y\text{Ga}_{1-y}\text{As}$,

InP, or $\text{In}_2\text{Ga}_{1-x}\text{P}$ layer, said layer being positioned on upper surface of a compound semiconductor substrate.

35. An enhancement mode metal-sulfide-compound semiconductor field effect transistor as claimed in claim 34 wherein the compound semiconductor substrate includes a GaAs based
5 semiconductor wafer.

36. An enhancement mode metal-sulfide-compound semiconductor field effect transistor as claimed in claim 34 wherein the compound semiconductor substrate includes a InP based semiconductor wafer.

37. An enhancement mode metal-sulfide-compound semiconductor field effect transistor as
10 claimed in claim 1, 13, 26, and 33 that may be integrated together with similar and complementary transistor devices to form complementary metal-sulfide compound semiconductor integrated circuits.

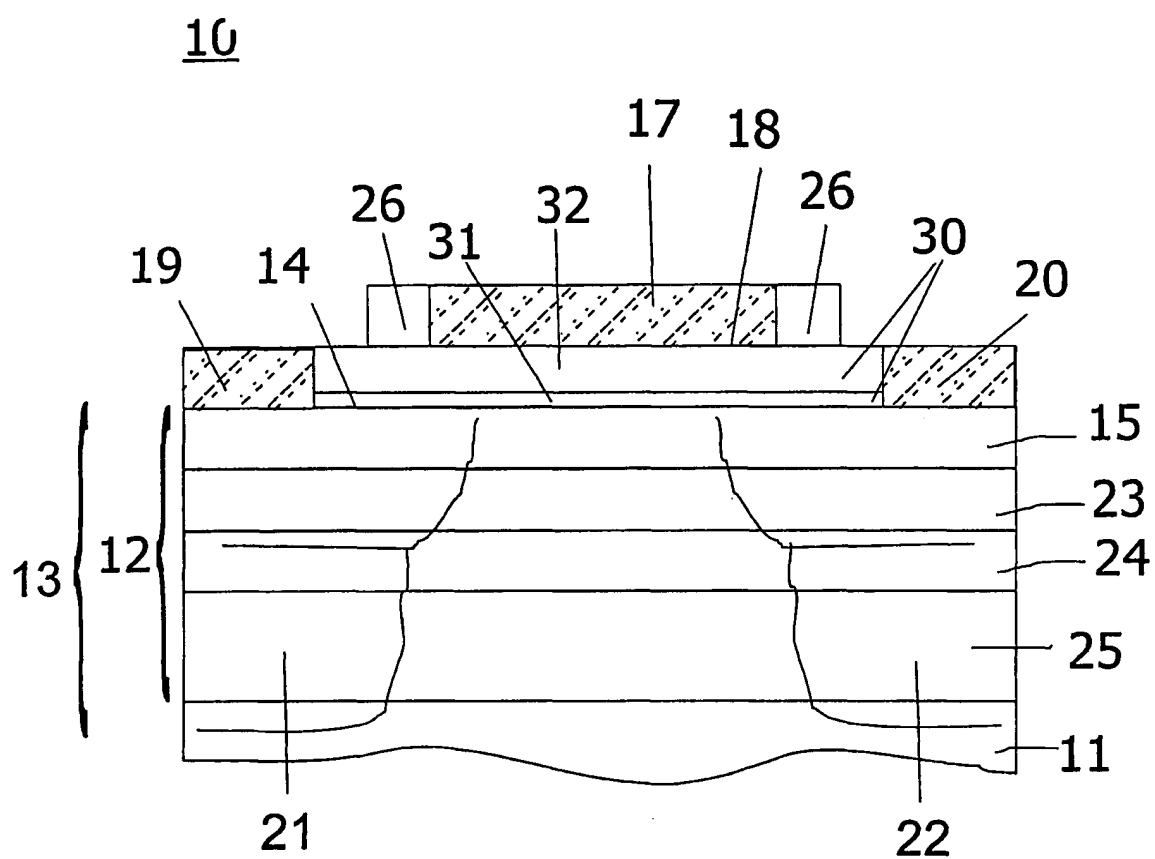


Figure 1

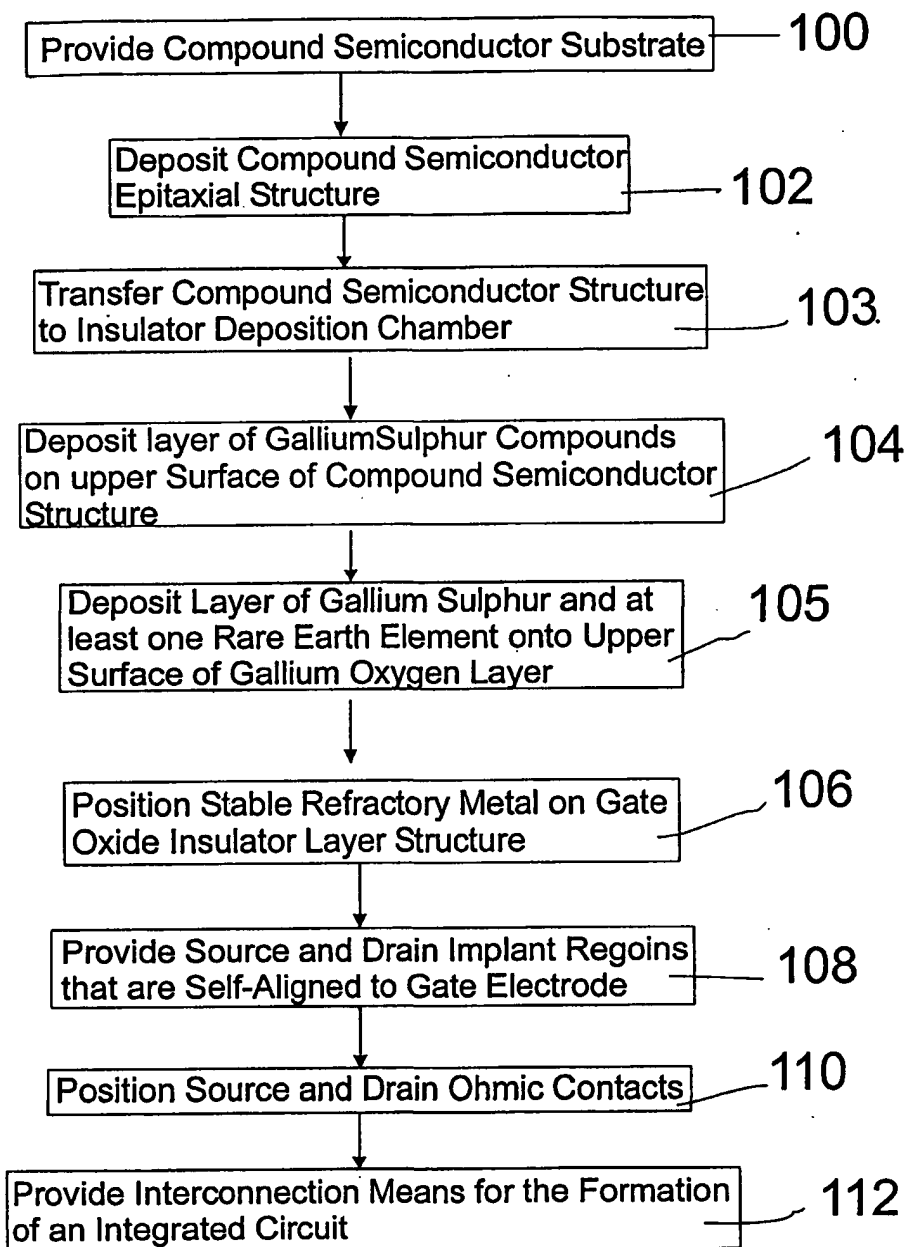


Figure 2

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US01/25259

A. CLASSIFICATION OF SUBJECT MATTER

IPC(7) : H01L 31/072, 31/109, 31/0328, 31/0336, 29/76, 29/94

US CL : 257/192, 194, 406, 410, 411, 412

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 257/192, 194, 406, 410, 411, 412

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

Please See Extra Sheet.

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 6,071,780 A (Okamoto et al.) 06 June 2000, (06/06/00) entire document.	1-26 ----- 27-37

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:	*T* later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
A document defining the general state of the art which is not considered to be of particular relevance	*X* document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
B earlier document published on or after the international filing date	*Y* document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
L document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	*G* document member of the same patent family
O document referring to an oral disclosure, use, exhibition or other means	
P document published prior to the international filing date but later than the priority date claimed	

Date of the actual completion of the international search

13 NOVEMBER 2001

Date of mailing of the international search report

20 DEC 2001

Name and mailing address of the ISA/US
Commissioner of Patents and Trademarks
Box PCT
Washington, D.C. 20231

Facsimile No. (703) 305-3230

Authorized officer

MINHLOAN TRAN

Telephone No. (703) 308-4919

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US01/25259

B. FIELDS SEARCHED

Electronic data bases consulted (Name of data base and where practicable terms used):

EAST

Search terms : field effect transistor or FET, compound semiconductor, gallium sulfide or gallium sulphur, gate
(insulator or insulating or dielectric)